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SULFUR HEXAFLUORIDE
IN
HIGH-POWER MICROWAVE SYSTEMS

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ATTN OF: RAAP

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TO: Holders of RADC-TDR-62-443, Sulfur Hexafluoride In High-Power Microwave Systems, by Vincent Vannicola

Reference is made to Figures 5 and 7. Through an error in printing these figures were transposed. The graph now appearing as Figure 7 should appear on page 8 as Figure 5. Graph now called Figure 5 should appear as Figure 7.

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ABSTRACT

Sulfur hexafluoride (SF_6) is being used extensively as a means of obtaining high peak power performance in waveguide systems. There is reason to believe that optimum efficiency is not currently being achieved in waveguide systems using this electronegative gas. This report reviews the available data on the use of SF_6 in microwave systems. Inconsistencies in these data are noted. For example, power ratios (breakdown power of SF_6 over that of air at normal pressures with all other parameters constant) are reported from a low of 3 to a high of 40. The mechanisms of these inconsistencies are discussed in terms of geometric configuration, contamination, localized hot spots, localized corona discharge, etc. Areas of future investigation are discussed.

PUBLICATION REVIEW

This report has been reviewed and is approved.

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1. INTRODUCTION

To date there is insufficient experimental data available on the microwave properties of sulfur hexafluoride (SF_6) and other dielectric gases. Most of the data that is available tends to be restrictive to very specific sets of parameters.

When very high power is transmitted down a waveguide, large electric fields are produced. In the waveguide some electrons are always present due to background radiation, field emission, and thermal emission. Under a high electric field the electrons are accelerated and if the incident field is sufficiently large, these electrons may acquire velocities necessary to knock out other electrons from neutral gas molecules. Secondary electrons are also emitted when field accelerated positive ions or photons strike the waveguide walls. As these processes repeat themselves, an abrupt increase in electrons results.

This rapid increase in electron concentration is manifested by an arc, at which point we have breakdown. There are, however, mechanisms which limit or suppress this process. These are (a) diffusion of the electrons to the waveguide walls; (b) attachment of the electrons to neutral gas molecules, thereby reducing their mobility to practically zero; and (c) recombination of an electron with a positive ion. All three of these mechanisms described involve the removal of electrons from the gap.

With the introduction of nonlinear fields, contamination, etc., these interrelationships become more complex. Rigorous analytical and experimental procedures are then required in order to obtain optimum efficiency in utilizing these dielectric gases for increasing the breakdown thresholds. This report will discuss some of the major points that may be responsible for the inconsistencies in breakdown using SF_6 in high-power microwave systems.

2. PRESSURE AND FIELD CONSIDERATIONS

In a waveguide with no discontinuities present the r-f breakdown voltage varies chiefly as a function of pressure. At pressures in the 1-20 mm Hg range, the breakdown voltage reaches a minimum at which only a few hundred volts will arc across a one-inch gap.[1] Such a pressure dependence is illustrated in Figure 1a. The exact pressure at which the minimum appears depends on frequency, waveguide size and many other variables.

At pressures below this minimum the gap becomes progressively more resistant to breakdown as illustrated in Figure 1a. This is due to greater efficiency in the removal of electrons which are produced by the high r-f electric fields. In this case the dominant electron removal mechanisms are diffusion under E-field forces. Here the reduction in pressure has increased the mean free path (distance electron travels between ionizing collisions) to an order of magnitude equal to or greater than the gap. An ionizing collision is defined as a collision between two or more particles from which a free electron emerges. As the pressure is further decreased the mean free path becomes longer, thereby rendering the electron removal mechanisms more efficient. The result is an increase in breakdown strength.

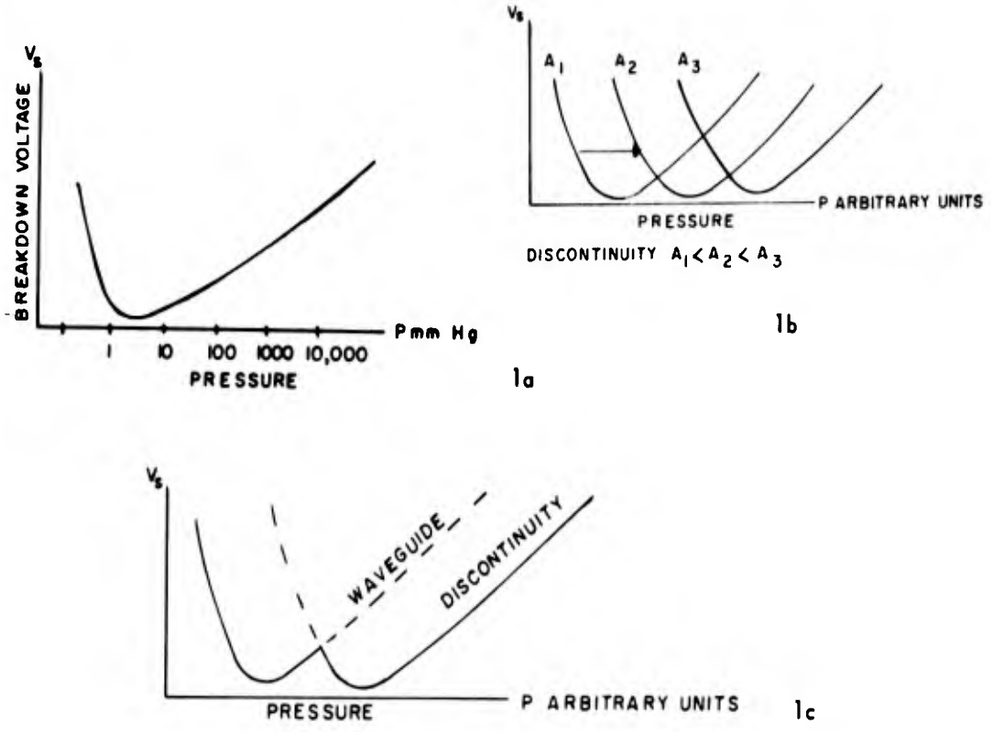


Figure 1. Breakdown as Affected by Waveguide with Discontinuities

Let us next consider the portion of the curve in Figure 1a which lies above the minimum 1-20 mm Hg range. Here we have increased the gas molecular density such that many of the field accelerated electrons undergo elastic (non-ionizing) collisions before they can acquire velocities necessary for ionization. This tends to suppress the average electron velocity so that higher voltages are needed to produce breakdown. If an electronegative gas such as SF_6 is used to fill up the waveguide then many of the free electrons will attach themselves to the gas molecules. Such an electron loss mechanism is called attachment. The electron charge is now transferred to a heavy molecule the velocity of which will not be appreciably accelerated by the E-field. This heavy ion does not produce any ionization and is neutralized when it drifts close to the waveguide walls or when it combines with a positive ion. As the density of such a gas is increased (through a pressure increase), attachment becomes more dominant resulting in a higher breakdown strength.

In the neighborhood of the minimum breakdown voltage none of the electron removal mechanisms have any significant efficiency. The molecular density is too high to permit effective diffusion and E-field removal of electrons, yet it is not high enough to establish any substantial rate of attachment. Furthermore, when the electron transient time, which is established by molecular density and gap distance, is greater than the half-period of the driving oscillation, electrons tend to become trapped within the gap. They still continue to multiply with each succeeding half-cycle. At this point, attachment to gas molecules becomes the dominant electron removal mechanism.

Let us now consider the effects of a transmission line discontinuity. Under such

conditions the electric field is non-linear, usually concentrated over a certain region and then diminishing at adjacent regions. At the low end of the pressure curve the electron loss mechanisms are aided since electrons are easily removed from the relatively small neighborhood of the high field concentration, where breakdown is most likely to originate. The removal mechanism here is diffusion and E-field forces. On the other hand, at the high end of the pressure curve, breakdown will occur at voltages lower than that for a uniform field because the higher E-field concentration increases the ionization rate through that portion of the gap. Unless the field is extremely nonlinear, an arc originating in the region of high field concentration will traverse the entire gap. The effect of such a discontinuity causes a shift in the curve as shown in Figure 1b.

Figure 1c illustrates the result of combining a uniform waveguide and a waveguide containing a discontinuity. Voltage breakdown for a given pressure is limited by the waveguide or the discontinuity, whichever is lower. The greater the discontinuity the greater the shift in the voltage breakdown-pressure curve. This can lead to a rather severe deterioration in the breakdown strength of the system.

It can be seen from Figure 1c that, except for high vacuum conditions, the breakdown voltage for typical configurations does not necessarily vary linearly with pressure as it does in uniform waveguide. As a consequence, a system containing a combination of uniform configurations and discontinuities of the type found in hybrid couplers, filters, and rotary joints has a breakdown power that may not vary as the square of the pressure. The application of the square-law relationship works reasonably well for uniform waveguide but may lead to erroneous results when a system of various components is under consideration. Information is available relating transition pressures with discontinuity controlled breakdown.[2]

Therefore, the effect of discontinuities is to decrease the breakdown voltage from that of uniform waveguide and also to invalidate the square-law principle. These effects hold true for normal pressures (around one atmosphere and above) and become progressively worse with larger discontinuities.

3. TEMPERATURE CONSIDERATIONS

The temperature of the dielectric gas must also be considered in conjunction with pressure. For a given pressure a temperature change due to electromagnetic losses will affect the gas density (number of gas molecules per cubic centimeter),[3] resulting in a change in mean free paths, ionization rates, attachment rates, and other properties. This results in a change in power-handling capability. Such a relationship is shown in Figure 2.

The effective pressure P_e normalized to room temperature is

$$P_e = \frac{P 293^\circ K}{T},$$

where T is the temperature in $^\circ K$. of the gas under consideration and P is the actual pressure.

When high skin losses are encountered in a localized region, the adjacent volume of gas is raised in temperature. Provision must be made to circulate the gas or it will heat up and cause a local decrease in breakdown strength.[4] Once an arc has started locally it usually traverses the entire gap to produce a failure.

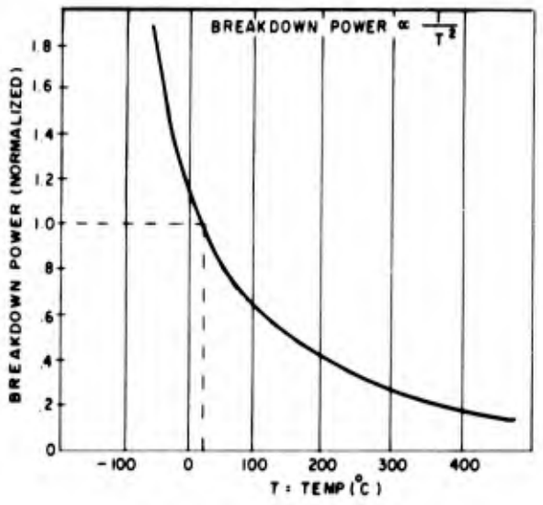


Figure 2. Relative Breakdown Power vs Temperature at Constant Pressure

At 150° *C*. SF_6 begins to undergo chemical decomposition, the effects of which are discussed in Section 4.

For gases such as nitrogen and oxygen, higher temperatures in the order of 1000° *K*. to 2000° *K*. will cause thermionic electron emission from the electrode surfaces. Since a significant number of electrons (ions) capable of leading to an avalanche become present, a reduction in either pulse width or peak power, or both, results. Only a formulative time lag is now required for breakdown*. The exact temperature at which this phenomenon exists depends on the work functions of the cathode (waveguide walls) material. Above 5000° *K*. the gas itself will thermally ionize, thereby producing electrons and positive ions throughout the gap. Here the gas itself becomes a conducting plasma and may be considered broken-down with no application of electric field. Breakdown at such elevated temperatures is of little concern since these conditions are rarely encountered in waveguide.

At very low temperatures, around –64° *C*., SF_6 shows a deterioration in power ratio for normal pressures. So far this has not been fully explained.[5] This degradation may be due to the gas sub-liming and forming crystals on the walls of the components. The result is a loss of breakdown strength through a decrease in the molecular density of the gas.

4. CONTAMINATION

Contamination effects must also be considered when using SF_6 or other heavy molecular weight dielectric gases, especially when their constituents include halogens. If a waveguide system is not sufficiently evacuated (pressure less than 1 micron Hg) prior to filling the system with SF_6, small quantities of air will cling to the walls of the system. Mere flushing of the system with SF_6 may not displace all the air. Pockets or layers of air present near the walls of a waveguide enable initiatory electrons leaving the walls to multiply through ionizing collisions with these air molecules. This leads to a small

* The time for breakdown to occur can be divided into two time lags, during which separate events take place. For a discussion of this subject see Appendix.

corona-like breakdown within the air gap which in turn breaks down the SF_6 molecules adjacent to this corona until complete flashover is encountered. Heat generated from this process also aids in the chemical breakdown of the adjacent SF_6 molecules. The broken-down SF_6 produces other impurities, including fluorine, having breakdown strengths less than that of air. As the SF_6 is broken down, the system will gradually deteriorate so that the power-handling capability becomes less than air. Still worse are the corrosive properties of such impurities which inflect permanent damage to components. For example, hydrofluoric acid would be produced if any water vapor were present in the system.

Richard C. Beitz of Cornell Aeronautical Laboratories has acquired a power ratio of 40 with SF_6 at S-Band under conditions of relatively uniform fields. The waveguide system used was first evacuated down to 1 micron Hg and then filled with one atmosphere of SF_6.

Most data have shown power ratios in the neighborhood of 7 to 10. However, there is not much evidence that any special effort was made[7] to evacuate the system down to the level of Dr. Beitz's setup. In fact, one of these figures represents a case where no attempt was made to keep the guide surfaces clean. Some of the data obtained are shown in the following table.

FREQUENCY	GEOMETRIC CONFIGURATION	BREAKDOWN POWER NORMAL PRESSURE & TEMP AIR	BREAKDOWN POWER NORMAL PRESSURE & TEMP SF_6	POWER RATIO	SOURCE OF INFORMATION
3000 MC Pulsed	1.5" x 3.0" waveguide system including components - typical	350 KW	15 MW	40	R.C. Beitz, Cornell Aeronautical Laboratories.[6]
2750 MC Pulsed .00045 duty	Plain 1.3" x 2.8" waveguide .5" hemisphere	06 MW	.9 MW	15	F. Arams, M. Freundlich, W. Peyser, Airborne Instruments Laboratory, Contract AF30(635)-2838.[5]
2750 MC Pulsed .00045 duty	Plain 1.3" x 2.8" waveguide with rounded point .25" deep, .1" diameter	9 MW	20 MW	2.2	F. Arams, M. Freundlich, W. Peyser, Airborne Instruments Laboratory, Contract AF30(635)-2838.[8]
X-Band	Test cavity, unevacuated and unclean surface		3:1	3	
9375 MC Pulsed .00048 duty	.9" x .4" waveguide	64 KW*	205 KW*	3.2	Sperry Gyroscope Contract NObsr-52227[7]
9375 MC Pulsed .00048	.9" x .4" waveguide containing 2 hemispherical bumps of radius .15" each	28 KW**	201 KW**	7.1	Sperry Gyroscope Contract NObsr-52227[7]
9375 MC Pulsed .00048 duty	Swayback in WR-90 from .4" to .012"	24.5 KW***	296 KW***	12	Sperry Gyroscope Contract NObsr-52227[7]

* Pressure 6.7" Hg abs
** Pressure 12.2" Hg abs
*** Pressure 20" Hg abs

Another contamination factor is the presence of dust in the waveguide system.[5] A reduction in peak power-handling capability down to one-tenth the theoretical breakdown level has been observed as a result of dust. Extreme care must be taken to assure a minimum of dust. Filtering and electro-static dust removers in conjunction with recirculating the gas fill may be desirable in some cases. Furthermore, an effort should be made to prevent dust from entering waveguide components while in storage. In such a situation the use of flange covers cannot be over-emphasized. At time of assembly the guide should be thoroughly cleaned.

Decomposition of the dielectric is also brought about by the presence of local hot spots which may be due to small regions in which there are great skin losses. Such losses can be brought about by dust, non-linear fields, and windows. (Besides producing thermal decomposition these hot spots aid the breakdown mechanisms through a local reduction in gas molecular density.) When these local temperatures exceed 150° *C*. the neighboring SF_6 will decompose into compounds of undesirable electrical and chemical properties as described above.

It should be mentioned here that many of these by-products are also toxic when inhaled.[8]

The exact temperature at which SF_6 undergoes chemical breakdown is dependent upon the waveguide material.[9] At 150° *C*. care must be taken in selecting waveguide material. In order of decreasing catalytic effect for SF_6 thermal chemical breakdown materials are:

. Silicon Steel	. Stainless Steel
. Steel	. Aluminum
. Brass	. Silver Plate
. Copper	. Quartz

Most of these materials cause chemical breakdown of SF_6 at temperatures from 150° *C*. to 200° *C*. The temperature for quartz is 500° *C*.

5. CORONA DISCHARGE

The behavior of a gas as affected by extremely non-uniform fields is shown in Figure 3. When fields of very high asymmetrical configuration are created, a discharge will result only at the region of high field intensity. The curve is a plot of low-frequency peak breakdown voltage versus gap spacing between a constant hemispherical point and a plane.

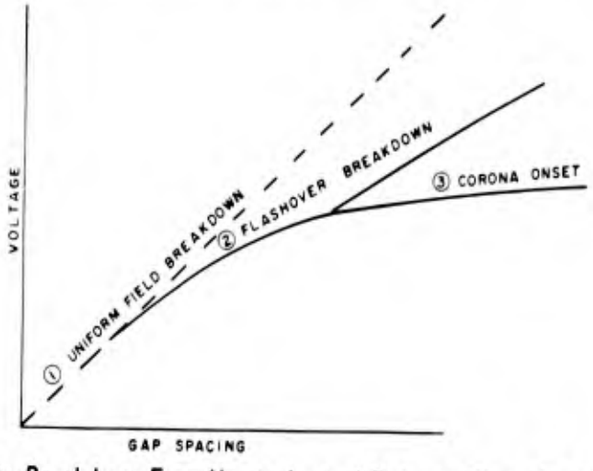


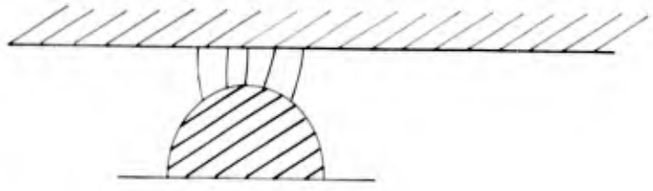
Figure 3. Breakdown From Hemispherical Point to Plane for 60-Cycle ac.

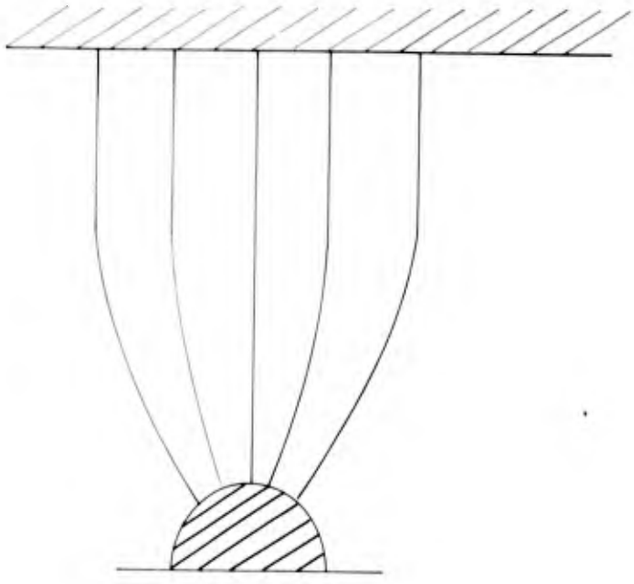
a. Region 1 of the curve (broken line) represents the breakdown voltage between two planes or between a plane and a very closely spaced hemisphere. In this case the field in the breakdown region between these two surfaces is approximately uniform. This is illustrated by Figure 4a. In this case breakdown coincides with that of a field with no discontinuity.

b. In region 2, (Figure 3) the electrodes are moved apart and the field starts to become non-uniform. Breakdown is initiated near the electrode of highest field intensity. However, a localized breakdown cannot occur without developing into a complete flashover.

c. As the electrodes are separated even further as shown in Figure 4b, the field becomes so asymmetrical that a discharge (corona) which originates at the region of high intensity cannot traverse the entire gap, (Region 3 of Figure 3). This is due to the insufficient field in the region of low intensity and therefore its inability to sustain the discharge. When the voltage across the electrodes is further increased, the field within the low intensity region will be strong enough to sustain the discharge and complete flashover will result.

4a., Approximate Uniform Field; Closely Spaced Electrodes.





4b. Non-uniform Field Intense at Small Electrodes.

Figure 4. Field Effects of a Hemisphere and Plane

6. MIXTURES WITH OTHER GASES

It is believed that when an electronegative gas is thoroughly mixed with a non-electronegative gas or a slightly electronegative gas such as dry air, the dielectric strength at first increases much more rapidly than the rate at which the dielectric gas is added. Data collected at Rome Air Development Center substantiates this relationship. (See Figure 5). This is due to the increase in attachment coefficient of the gas mixture and its ability to remove electrons before they can avalanche. Since an electron avalanche grows exponentially, the removal of an electron in its pre-avalanche stages is equivalent to the removal of its exponential product. This exponential relationship is discussed in more detail under the topic "Formulative Time Lag" in the Appendix. However, when high purities of SF_6 are applied to properly evacuated systems a question is raised as to whether the dielectric strength undergoes a rapid increase in the neighborhood of the 100% concentration point. Figure 6 shows two curves in which present data is based on curve 1. (The manufacturer guarantees

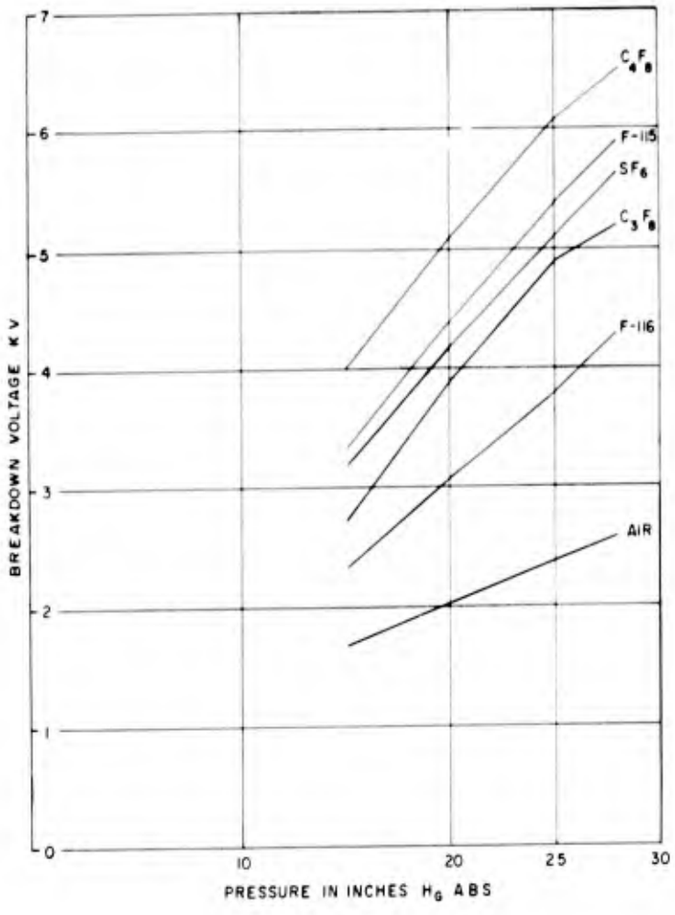


Figure 5. Breakdown Voltage vs Pressure for Different Percentages of SF_6 Mixed in Air (Across a Spark Plug)

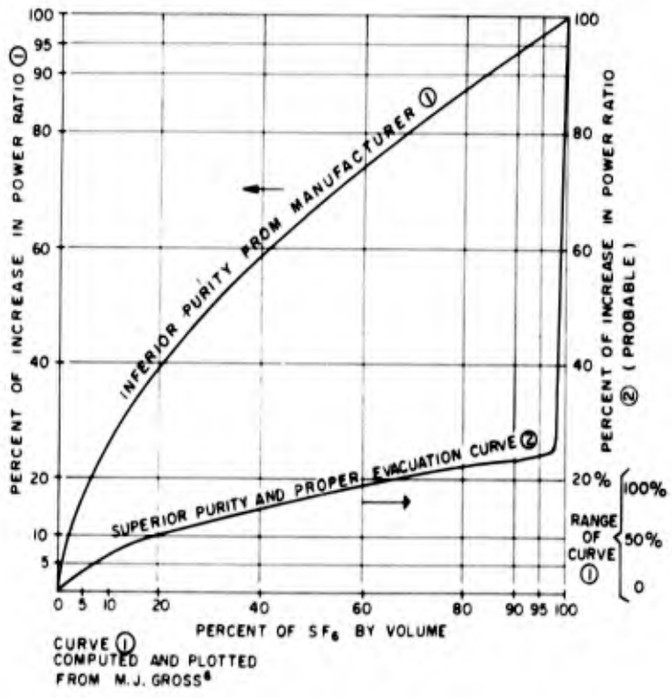


Figure 6. Effect of Air Mixture on Power Ratio of SF_6 for 60-Cycle a-c, 1 Atmosphere Pressure, Electrode Configuration 1.0" Spheres, .25" Separation

only SF_6 to be 99% pure.) If a rapid increase in dielectric strength is obtained at higher purities of SF_6 then curve 2 would hold. In drawing this second curve it is assumed that the dielectric strength suddenly doubles at mixtures of 100% SF_6. Both curves have been normalized to their respective maximum power-handling capability. If such a relationship does exist then the need for obtaining higher purities of SF_6 along with proper evacuation becomes apparent.

There seems to be some doubt as to the true power ratio for high purity SF_6. It was mentioned that power ratios of 40 were obtained when the air in the S-Band waveguide system was evacuated down to 1 micron before filling with SF_6. Now, if curve 1 in Figure 6 holds true, comparable power ratios should have been reported from other sources, even if the SF_6 used was only 95% pure. This seems to indicate that the true relationship is really illustrated by curve 2.

These findings certainly warrant further investigation. There may be a region very close to the 100% SF_6 point where the power ratio takes a sharp rise (curve 2 of Figure 6). In experimental evaluations, the sharp rise close to the 100% point would pass by undetected if purity tolerances are held to within only a few percent. If such an increase in power ratio does exist, mixing with air would have a pronounced degradation on the merits of high purity of SF_6.

7. OTHER DIELECTRIC GASES

The dielectric strengths of other gases were also measured at Rome Air Development

Center. These results are shown in Figure 7 along with those of SF_6 and dry air. Such data was taken across a spark plug gap at 60 cycles a-c.

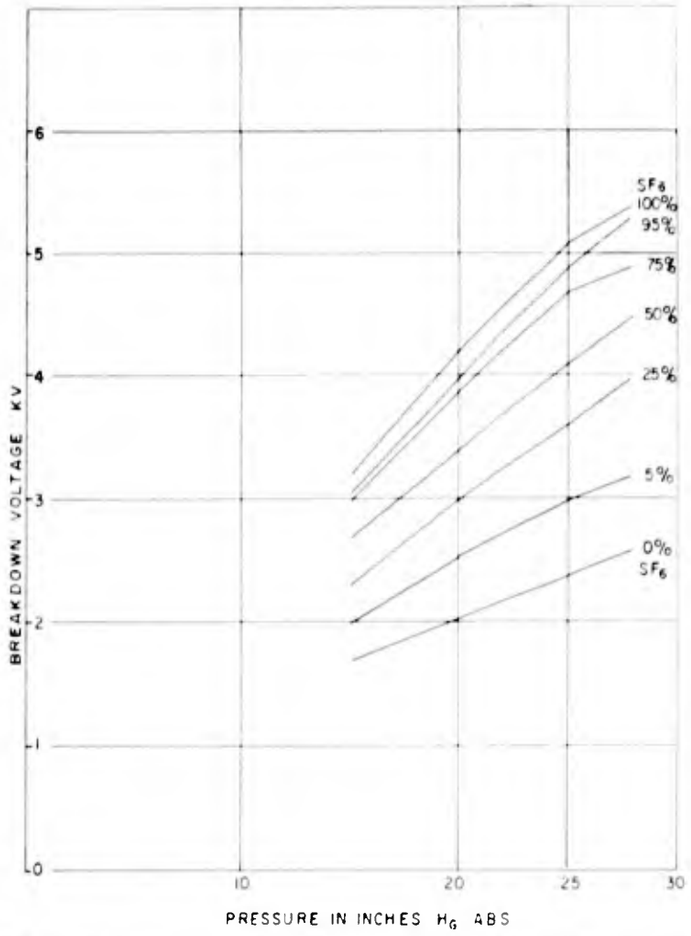


Figure 7. Breakdown Voltage vs Pressure for Different Dielectric Gases (Across a Spark Plug)

8. CONCLUSIONS

One major disadvantage of SF_6 is its chemical disassociation. Small corona and local hot spots which can normally exist unnoticed in air gradually decompose the SF_6, degrading breakdown strength and possibly inflicting damage to the components. Such troublesome areas cannot be tolerated if SF_6 is to be used. These phenomena may also have some bearing on the wide-spread variation of results thus far obtained for SF_6.

Geometric configurations play an important role in the breakdown field -- pressure relationships. Waveguide systems with non-uniform configurations do not behave in accordance with the rule that breakdown power is proportional to the square of the pressure at and above one atmosphere. In addition, the power ratio for SF_6 compared with air also varies with respect to the geometrical configuration. At pressures above one atmosphere, both the degradation in breakdown power and the effects of corona onset become generally more severe with increasing orders of discontinuities.

Pure SF_6 may yield greater performance characteristics than is generally believed possible. A substantial increase in power ratio may result when the amount of SF_6 is greater than 99% and approaching 100%.

In an experimental setup, factors such as temperature, mixtures, purging, dust, purity, and inhomogenuity of the mixture must be known and controlled in order to establish more accurate data on the r-f properties of SF_6.

9. RECOMMENDATIONS

The following subjects pertaining to SF_6 are recommended for future investigation towards improving the breakdown power of microwave transmission systems.

The first is a vacuum tube approach for fabricating microwave components with relatively large discontinuities. Since components with large discontinuities impose lower breakdown power limits in a waveguide system, a vacuum tube fabrication technique applied only to such components may reduce the effect of such limitations. An increase in power-handling ability at such critical areas would allow the rest of the system to be treated in a more conventional manner. Such a technique would insure high degrees of SF_6 purity within such critical components. Some of the advantages and disadvantages of such an approach are as follows:

Advantages

. Purity can be maintained by sealing off the gas, thereby keeping power ratio at its ultimate.

. Breakdown power of the system can be increased by raising the breakdown strength of the limiting components by a substantial amount.

. These components can be factory-made, eliminating this task for the field.

. Dust-free operation would be achieved insofar as these critical components are concerned.

. All other components, including waveguides, whose geometric configuration is more uniform can be treated less critically and still achieve optimum system performance.

Disadvantages

. Windows to seal off components may become the limiting element.

. Component material may gradually contaminate the gas or yield corrosion product surface coating or dust in the sealed regions.

. Cost of component will increase.

Another area of investigation should be the use of very pure SF_6 as opposed to mixtures of SF_6 with other less costly gases, such as dry air or nitrogen. Effects of mixture, power ratio, and cost should be experimentally evaluated and analyzed in order to derive greatest advantages through this approach. The use of other dielectric gases, such as C_4F_8 and C_3F_8 should also be investigated. Both these gases have molecular weights higher than SF_6, but their breakdown by-products include carbon.

The use of static electric and magnetic fields for ion sweeping at localized points where r-f fields are strongest may be effective in increasing breakdown power. This area certainly warrants looking into in that it may have some effect on corona.

The effects of circulating the gas through the waveguide system should also be considered. Such a scheme will improve the dielectric strength from the following viewpoints:

Cooling. It will reduce the degree to which local hot spots may grow. This would decrease locally the effects of:

- Gas molecular density decrease
- Contamination due to chemical decomposition
- Thermionic emission from waveguide surfaces.

Sweeping. The removal of ions from a region of relatively high concentration would be accomplished. In order to break down the region, a higher voltage is needed so that ion production may again overcome the rate of removal.

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APPENDIX

CONSIDERATIONS FOR PULSED POWER

To illustrate the effect of initial electrons on the establishment of an electron avalanche leading to voltage breakdown, we shall investigate certain events from which a mathematical analysis can be made. Similar treatments can be found in many publications.[3]

For breakdown to occur, a very large build-up of ionization is required. In order for such a build-up to take place, a finite time must elapse from the instant that voltage is applied. This time lag can be divided into two parts, namely, statistical time lag and formulative time lag which shall be discussed below.

Some of the more important events leading to breakdown occur in the following order upon application of high voltage.

1. Statistical Time Lag

a. First, a rate of electron production must exist within the gap. Of these electrons a certain portion must also become located in such a way that they can multiply through ionizing collisions and thereby lead to an avalanche. The rate at which this portion of electrons is produced shall be designated by β. Variables affecting this rate include field emission, photo emission, radioactive sources, thermionic emission, and other electron producers located in regions where these electrons can easily lead to an avalanche. Such regions would usually be near the cathode.

b. After an electron is located in a position favorable to lead to breakdown, it may or may not multiply into a steady current. The probability (P) that such an electron will lead to breakdown is dependent upon the magnitude of the applied voltage, pressure, and geometrical configuration of the electrodes. For the threshhold voltage at which breakdown just occurs this probability factor is zero; however, with increasing voltage (P) approaches unity.

The two factors (β, P) just discussed determine that part of the time lag that is based on statistical events. The average time for the appearance of an electron that can finally lead to breakdown shall be designated by T_s and is related to β and P by

$$T_s = \frac{1}{\beta P}. \tag{1}$$

Also, if β and P are independent of time, then the probability that a gap will break down in an interval of time dt, is

$$dP_e = \beta P dt. \tag{2}$$

If we observe (n_o) gaps in an experiment, and we wish to find the number of gaps (n) at some time (t) that have acquired the necessary electron which will lead to breakdown, we set the increase of these gaps (dn) that can break down during the time interval dt to be

$$dn = (n_o - n)\, dP_e = (n_o - n)\, \beta P dt \tag{3}$$

where ($n_o - n$) represents the number of gaps remaining that haven't acquired such an electron.

Integration of (3) gives

$$ln\ (n_o - n) = -\beta P t + K \quad (K = \text{constant of integration}). \tag{4}$$

To solve for K, we set the initial conditions $n = 0$ when $t = 0$. Substitution into equation (4) leads to a solution for K,

$$ln\ (n_o) = K.$$

Equation (4) becomes

$$ln\ (n_o - n) = -\beta P t + ln\ (n_o)$$

which can be expressed

$$(n_o - n) = n_o\ e^{-\beta P t}.$$

The number of gaps (n) which have acquired an electron that can lead to breakdown within the time (t) is therefore

$$n = n_o\ (1 - e^{-\beta P t}). \tag{5a}$$

Substitution of (1) gives

$$n = n_o\ (1 - e^{-t/T_s}). \tag{5b}$$

Equation (5) shows that a decrease in β (rate at which electrons are produced in a favorable location that will lead to breakdown) and/or decrease in P (probability that such an electron can lead to breakdown) will increase T_s, the statistical (average) time lag and decrease n, the number of gaps that will lead to break down at a particular time. With an increase in T_s one can go to longer pulse widths or higher peak powers or both before the same number of breakdowns will occur. This discussion can be applied to pulsed power simply by regarding the gaps as a pulse train of which each pulse is considered an individual gap. Then, for n_o pulses of pulse width (t) the number of pulses (n) that can lead to breakdown is

$$n = n_o\ (1 - e^{-t/T_s}).$$

2. Formulative Time Lag

After a gap (or pulse) has produced an electron that can lead to breakdown, another time interval is required for sparkover to occur. This time interval is called the formulative time lag and is the time necessary for the electron to multiply through ionizing collisions across the gap.

To derive an expression representing this multiplication effect let us introduce another constant (a) which shall be defined as the number of electron-producing collisions which an electron makes in traveling a unit length across the gap. The constant (a) is dependent mainly on pressure, the electric field $\frac{dv}{dx}$, and the type of gas used.

For a given set of conditions the increase in electron current $di_e(x)$ across a sector dx

of the gap is

$$di_e(x) = ai_e(x)dx \tag{6}$$

the positive direction of x being towards the anode.

To obtain an expression for the electron current $i_e(x)$ we integrate

$$\frac{di_e(x)}{i_e(x)} = a\,dx$$

which gives us

$$ln\, i_e(x) = \int_o^x a\,dx + K.$$

This can be expressed as

$$i_e(x) = e^k \exp\left(\int_o^x a\,dx\right) \tag{7a}$$

For uniform fields a is constant and so $\int_o^x a\,dx = ax$.

The electron current at the cathode, **i.e.**, at $x = 0$, **is some constant** $i(o)$ which depends on cathode material, space charge, temperature, and field strength. It is that current whose electrons can lead to breakdown as shown in the discussion on statistical time lag.

At $x = 0$, $i_e(x) = i(o)$ = constant, equation 7a becomes

$$e^k = i(o). \tag{7b}$$

Therefore the electron current at a distance x from the cathode is

$$i_e(x) = i(o) \exp\left(\int_o^x a\,dx\right). \tag{7c}$$

Now the change in positive ion current $i_+(x)$ across a sector of gap dx is

$$di_+(x) = -ai_e(x)dx. \tag{8}$$

Substitution of 7c leads to

$$di_+(x) = -i(o) \exp\left(\int_o^x a\,dx\right)a\,dx.$$

Integration gives

$$i_+(x) = -i(o) \exp\left(\int_o^x a\,dx\right)+K. \tag{9a}$$

To solve for K we set $i_+(x) = 0$ at the anode. The length between cathode and anode must therefore be specified as some value δ. At $x = \delta$ the positive ion current is

$$i_+(\delta) = 0$$

and substitution into (9a) solves for K

$$K = i(o) \exp \left(\int_o^{\delta} a dx\right). \tag{9b}$$

This gives

$$i_+(x) = i(o) \left[\exp \left(\int_o^{\delta} a dx\right) - \exp \left(\int_o^{x} a dx\right)\right] \tag{9c}$$

for the positive ion current.

The total current across the gap is the sum of equations (7c) and (9c):

$$i = i_e(x) + i_+(x) = i(o) \exp \left(\int_o^{\delta} a dx\right). \tag{10}$$

For a uniform electric field $i = i(o)e^{a\delta}$.

Since the build-up of current across the gap is an exponential function of a, and since this build-up occurs over a time interval which we call formulative time lag, an increase in a will reduce the time required for reaching a particular current. Breakdown therefore occurs with shorter pulses and lower peak powers.

The introduction of an electronegative gas such as SF_6 reduces the effect of a in that a percentage of electrons are now lost through attachment to gas molecules and these electrons can no longer contribute to the exponential build-up of current across the gap.* This enables the use of longer pulses and higher peak power. We are not so much concerned with secondary effects because at microwave frequencies the transient times of charged species are much greater than the half-period involved. This renders secondary effects negligible.

A point of consideration which can have a serious effect on a gas whose chemical breakdown products are electrically undesirable is the statistical time lag. In a series of pulses of which the pulse width is just under the average time lag, a small number of pulses will break down at a random rate.

Although this small number of discharges does not affect such gases as air, it will gradually deteriorate electrical performance when it occurs with a dielectric gas.

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* Special notice should be made of this effect when it occurs with an initiatory electron. When an electron is captured just after leaving the cathode before it can multiply, the number of electrons actually removed becomes $\exp \left(\int_o^{\delta} a dx\right)$.

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Unclassified Report

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2. Dielectrics
3. Electric Arcs
I. Vannicola, V.
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